Bubbles and Acoustics Communications Experiment: The Acoustical and Physical Characterization of Bubble Plumes

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LONG-TERM GOALS

The long-term objectives are to study the role of bubble production and bubble distributions within high air void fraction whitecaps and sub-surface bubble plumes on acoustical scattering at the ocean surface and the generation of noise by bubbles. An additional goal is to relate bubble production and plume properties such as penetration depth and acoustical scattering strength to the state of the ocean surface wave field.

OBJECTIVES

The objectives of the research are to (1) relate the acoustical scattering from high void fraction bubble plumes to measured plume properties, (2) determine the relationship between specific, measured plume properties, such as penetration depth, plume volume, plume void fraction and bubble size distributions to surface wave conditions and (3) relate bubble production within plumes to the generation of ambient noise.

APPROACH

We have employed two strategies to achieve the research objectives. The first is to conduct a series of wave tank studies in the hydrolics laboratory glass flume at SIO. These laboratory experiments were designed to study the basic physics of air entrainment and bubble production within plunging breakers. These experiments are complete, and the results are described below.

The second strategy is to make open-ocean measurements of whitecaps. An open-ocean experiment is scheduled for deployment in the Woods Hole Oceanographic Institution Underwater Acoustics Observatory of Martha's Vineyard during October and November of 2002. The experiment (called Surface Processes and Acoustic Communications 2002, or SPACE02) is being hosted by Dr. James Preisig at WHOI who will deploy underwater acoustic sources and hydrophone arrays to study surface, bottom and volume acoustic channel properties simultaneously with our whitecap measurements (described below). Dr. David Farmer from the University of Rhode Island and Dr. Svein Vagle from the Institute of Ocean Sciences, British Colombia will also participate. Their plan is to also study surface processes, but at length and time scales an order of magnitude longer than our measurements. Our whitecap measurements taken together with the extensive marine boundary layer characterizations of Farmer and Vagle will provide a complete surface characterization.

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The long-term objectives are to study the role of bubble production and bubble distributions within high air void fraction whitecaps and sub-surface bubble plumes on acoustical scattering at the ocean surface and the generation of noise by bubbles. An additional goal is to relate bubble production and plume properties such as penetration depth and acoustical scattering strength to the state of the ocean surface wave field.

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The core sensor system for the whitecap studies is the Advanced Plume Imaging System (APEX), developed and funded by a DURIP award through ONR. APEX will be deployed with acoustic wave field meters and a blimp-mounted camera to characterize the 2D surface wave spectrum and the distribution and rates of wave breaking.

APEX is a multi-sensor package designed to probe the structure of dense bubble plumes directly beneath ocean whitecaps on several simultaneous scales. It consists of two surface-following platforms deployable in high sea states to measure internal and macroscopic plume properties. The instruments on both frames include an optical bubble counter, an array of conductivity sensors, a conductivity/temperature sensor, an acoustic Doppler velocity profiler, an acoustic system for measuring plume scattering cross-section, and an underwater video camera. These sensors will simultaneously measure the bubble size distribution and void fraction of air within whitecap plumes, the size of the plumes and scaling of plume size with sea state, the acoustical roughness scales of the plume boundaries and the noise radiated during plume formation.

WORK COMPLETED

During the past 12 months, two series of experiments have been conducted in the seawater wave flume (33 m long, 0.5 m wide, 0.6 m deep) at Scripps Institution of Oceanography. Wave packets were generated at one end of the flume using a computer-controlled wave paddle, which produced plunging breakers approximately 10 cm in height. The amplitude and phase of the wave-packet frequency components were generated so that they added constructively at the wave break point, producing a breaking wave. Breaking events were studied with a high-speed video camera and front and back lighting to produce images of the complicated two-phase flow occurring a few centimeters (2.5-18 cm) away from the glass-walled side of the flume. From this work, we have been able to determine the scale dependence of bubble creation mechanisms in breaking waves, as described in the next section.

In addition, the preparation work leading up to the SPACE02 deployment is almost complete. The APEX systems have been constructed and passed their engineering trial deployments in laboratory tank facilities and the surf zone. All data acquisition and instrument-controlling computers have been programmed, housed and tested. Two of the main technical challenges were to synchronize data streams from third-party instrument systems and network all systems so that they can be monitored and controlled remotely. Both of these objectives have been achieved.

RESULTS

The significant results for this fiscal year have come from the laboratory wave-tank experiments, which are complete. Using the data from these experiments and our prior open-ocean whitecap studies, we have been able to make a fundamental advance in our understanding of air entrainment and bubble formation in breaking waves. We found that there are two distinct mechanisms controlling the size distribution of bubbles, depending on bubble size. Turbulent fragmentation determines the size distribution for bubbles larger than about 1mm radius, resulting in a bubble density proportional to bubble radius to the power of $-10/3$. Smaller bubbles are created by jet and drop impact on the wave face with a $-3/2$ power scaling law. The length scale that separates these processes is the scale at which the forces of turbulent fragmentation are balanced by bubble surface tension, also known as the Hinze scale. This fundamental property of the bubble spectrum is illustrated in Figure 1. The figure shows numbers of bubbles (per cubic meter of water per micro-meter radius increment) plotted versus bubble radius on a log-log scale. The uncertainty in bubble count has been estimated, and the standard deviation of the mean bubble count is indicated by the vertical bars running through each data point. Solid lines have been added to the figure to show the scaling laws of radius –3/2 and –10/3 for bubbles respectively smaller than and larger than the Hinze scale, which is about 1 mm in this figure.

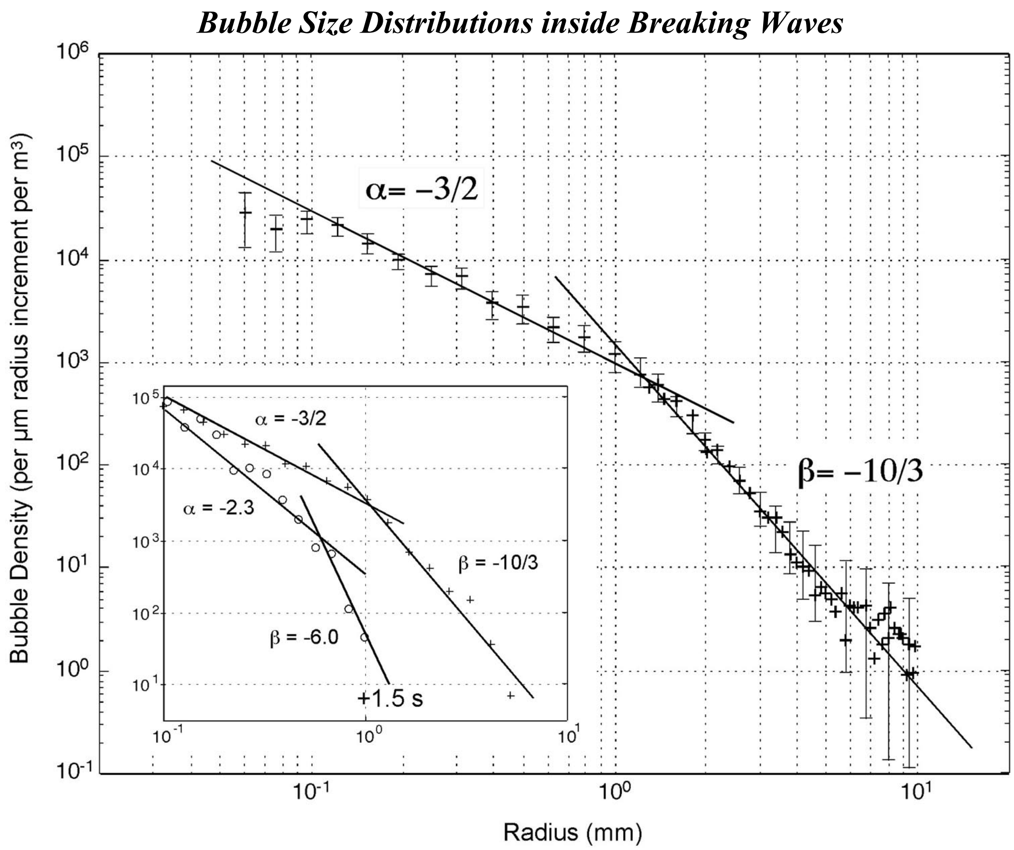

Figure 1. The figure shows the bubble density (number of bubbles per cubic meter per micrometer radius increment) as a function of bubble radius at the end of the active phase of plume creation. Bubbles smaller than about 1 mm scale as radius to the power of -3/2 and bubbles larger than 1 mm scale as radius to the power of -10/3. The figure inset shows the evolution of bubble density with time. Both power law scale laws increase with increasing time.

There are three important quantative findings that support our findings. The first is that the transition between bubbles stabilized by surface tension and bubbles subject to fragmentation by turbulence results in a change in the power law scaling of bubble size from –3/2 to –10/3. The transition between the scaling laws occurs at bubble radius equal to the Hinze scale, which varies from about 0.5 mm to 1.5 mm for open-ocean whitecaps. We have observed evidence of the Hinze scale in bubble size spectra taken from breaking waves in the laboratory, the open-ocean, and the surf zone, implying a common mechanism operates within waves occurring in these three very different environments. In addition, the turbulent dissipation rate within the laboratory waves implied by the observed Hinze scale is consistent with measurements of the dissipation rate within breaking wave crests made by Melville and his co-workers.

The second significant quantative result is the detailed observation of bubbles in the process of fragmenting. We were able to estimate the Webber number, Reynolds number and probability density of bubble eccentricity for a number of individual fragmenting bubbles within a breaking wave crest. Theoretical predictions of these variables based on prior work in the literature (including an important, recent contribution by Garrett, Li and Farmer) are in good agreement with our observations, which supports the idea that the population of bubbles larger than the Hinze scale is controlled by turbulent fragmentation.

The third result is the excellent agreement between the bubble size distribution scaling law predicted by Garrett, Li and Farmer (radius to the power of –10/3) for bubbles fragmented by turbulence and our observed distributions.

The results of the other major effort for the year (preparing for the SPACE02 experiment) will be reported next year after the experiment at Martha's Vineyard in November.

IMPACT/APPLICATIONS

The full impact of the SPACE02 experiment will not be realized until the experiment's completion later this year. There are a number of significant impacts arising from the bubble creation work and our discovery of simple scaling laws for bubble number density separated by a length scale that depends only on the turbulent dissipation rate. One of them is an opportunity to understand and model the fundamental physical processes leading to the –5/3 power law scaling of the wind-driven, oceanic ambient noise level with frequency. This property of oceanic noise, known for over 50 years as the Knudsen spectrum, is not well understood. Since the noise radiated by whitecaps is driven by bubble creation rates, our new understanding of bubble formation processes in whitecaps will provide new insight into the origin of the Knudsen spectrum. The results also have important application to modeling the bubble-mediated transfer of greenhouse gases and aerosol production, both important for global climate change.

RELATED PROJECTS

The work for the SPACE02 experiment has been undertaken in close collaboration with Dr. James Preisig at the Woods Hole Oceanographic Institution who is hosting the experiment, and Dr. David Farmer at the University of Rhode Island and D. Svein Vagle at the Institute of Ocean Sciences, British Colombia.

PUBLICATIONS

Grant B. Deane and M. Dale Stokes, "Scale dependence of bubble creation mechanisms in breaking waves", Nature **418** p.839-844 2002.

Grant B. Deane and M. Dale Stokes, "A robust single cable sensor array for oceanographic use", IEEE J. Ocean. Eng. *in press* 2002.